Halo Studies for the ESS & Linac4 (CERN) Front-Ends

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Outline

- Simulation of statistical errors with IMPACT,
- the lattices,
- transverse errors (quadrupole gradient),
- longitudinal errors (phase & field gradient),
- halo development through statistical errors (as opposed to initial mismatch),
- particular problems for proton linacs with low-energy beam choppers.

Introduction

- After halo studies with initial mismatch, statistical error analysis is the last stage in the machine design,
- realistic input distributions (measured or simulated RFQ output) should be used,
- location, amount and probability of losses in presence of errors can be assessed,
- losses and ε growth then define the tolerances for the RF systems, quadrupole gradients, alignment precision, etc.,
- output phase and energy jitter has to be limited if the beam is injected into subsequent accelerators.

Approach

Assumption: the main statistical phase & gradient errors are grouped according to power supplies.

pre-processing → **Impact** → **post-processing**

- define error types (RF, quadrupole, alignment, etc),
- define groups of errors according to power supplies (e.g. gaps per RF tank, quadrupoles per amp., etc.), and their amplitude (x% field error, x$^\circ$ phase error),
- modify the original input file and create n scratch directories with different error sets,
- submit n jobs to the computing cluster,
- repeat for several error amplitudes with the same (scaled) error sets.

- find max. and average $\varepsilon_{r.m.s.}$ increase (compared to no-error case) in all planes,
- max. phase & energy deviation along the linac,
- probability plot for phase & energy deviation at the end,
- max. and average deviation from the nominal beam radii,
- max. and average losses,
- location of losses.

Simulated Lattices

ESS (front-end)

RFQ output distribution 2.5 MeV 57 mA 280 MHz → chopper line → 2 DTL tanks → 20.3 MeV

chopper line: *6 buncher cavities, 13 quadrupoles, length: 3.11 m (40 $\beta\lambda$)*
DTL: *2 RF systems, 82 gaps, 83 quadrupoles, 11 m*

Linac4 (front-end)

RFQ output distribution 3.0 MeV 30 mA 352 MHz → chopper line → 2 DTL tanks → 24.9 MeV

chopper line: *3 buncher cavities, 11 quadrupoles, length: 3.73 m (54 $\beta\lambda$)*
DTL: *2 RF systems, 77 gaps, 78 quadrupoles, 9 m*

Linac4 (total)

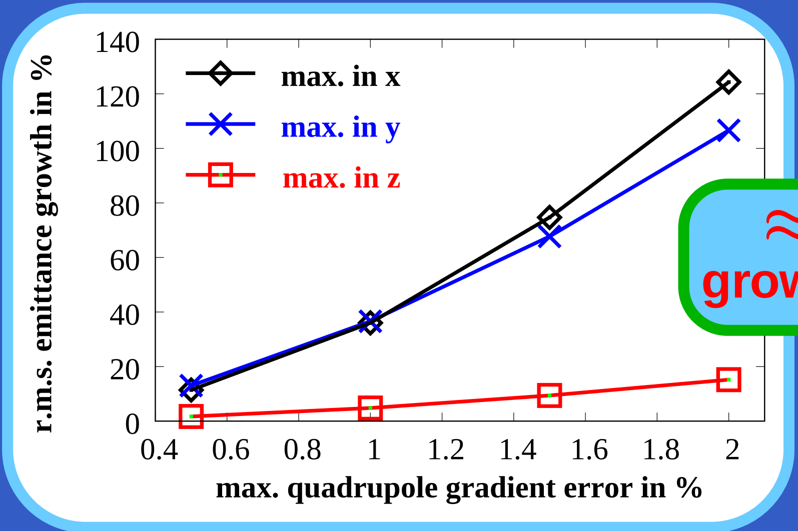
→ 1 DTL tank → 3−gap CCDTL → 4−gap CCDTL → 120 MeV

chopper line: *3 buncher cavities, 11 quadrupoles, length: 3.73 m (54 $\beta\lambda$)*
DTL: *3 RF systems, 106 gaps, 107 quadrupoles, 15.1 m*
CCDTL: *10 RF systems, 37 3/4-gap tanks, 37 quadrupoles, 47.6 m*

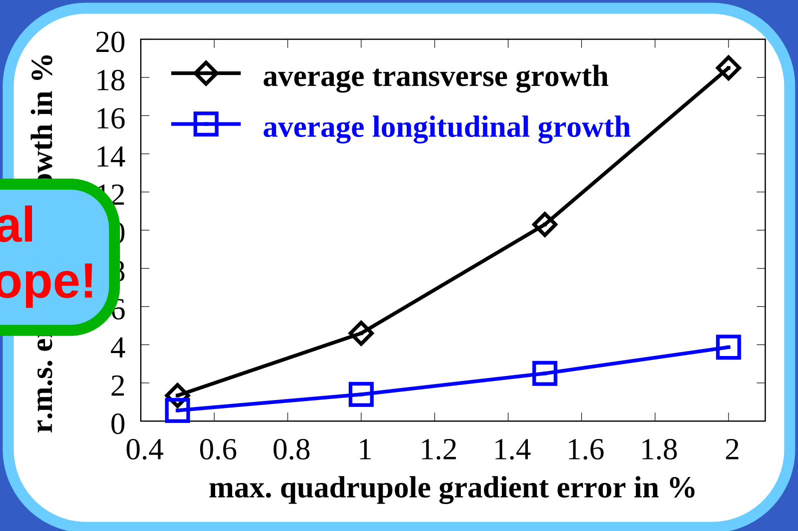
Transverse Errors (emittance increase)

- Generally quadrupoles are powered in groups of 4 to 5 magnets,
- one power supply per quadrupole is used in the chopper line and for the first three and last three magnets of DTL tanks,
- for the full Linac4 500 error sets with 50000 particles are used ($\approx$ 14 h on 30 processors) for each error amplitude.

Additional emittance growth for the full Linac4:



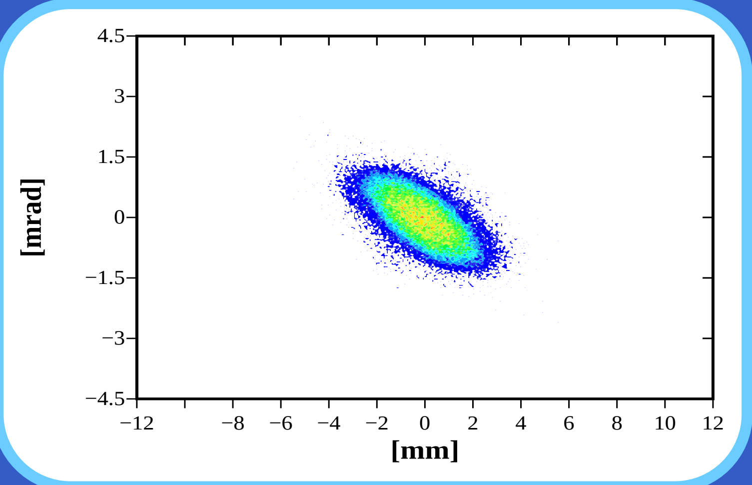
≈ equal growth slope!



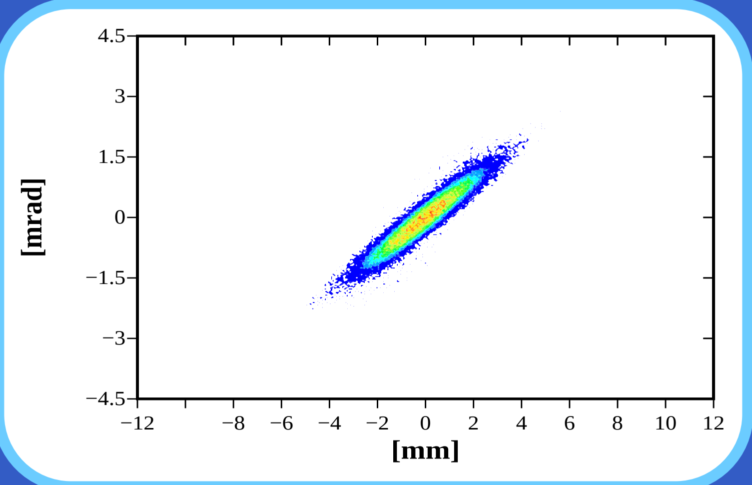
maximum r.m.s. emittance increase

average r.m.s emittance increase

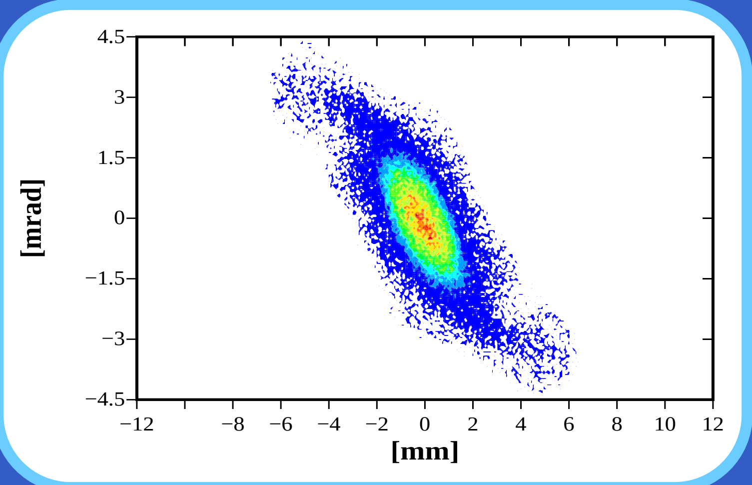
Transverse Errors (phase space)



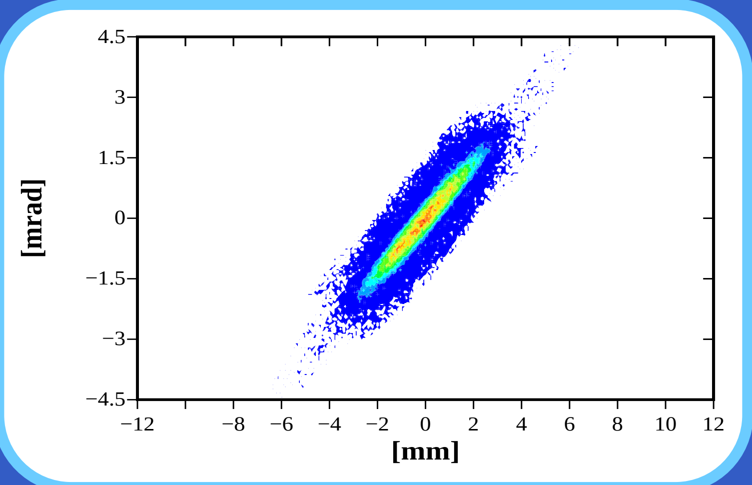
x-x’, average case for 1% gradient variation, full Linac4



y-y’, average case for 1% gradient variation, full Linac4



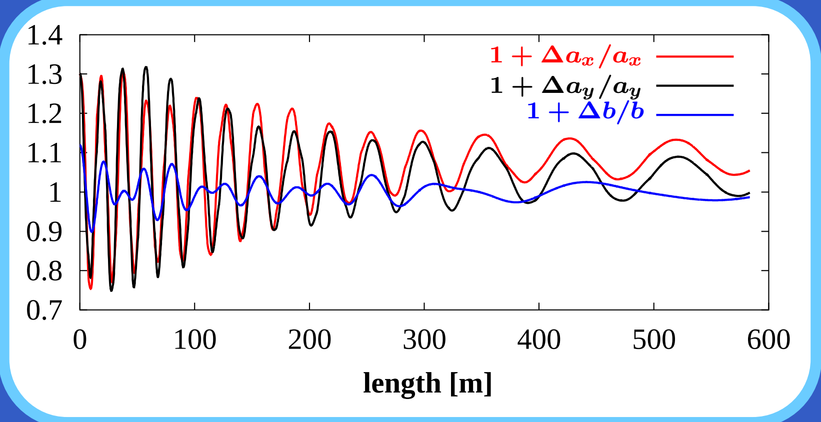
x-x’, worst case for 2% gradient variation, full Linac4



y-y’, worst case for 2% gradient variation, full Linac4

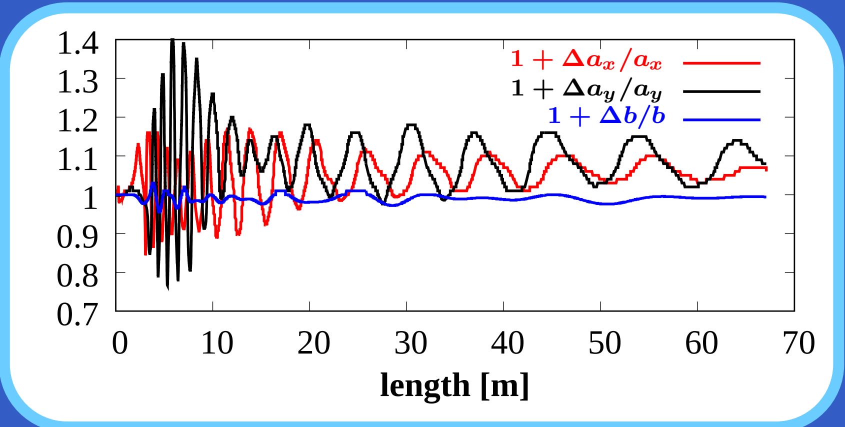
Transverse Errors (radial deviation)

Halo in a nutshell: Halo particles are generated by parametric resonances between single particles and the oscillations of a mismatched beam core.



30 % fast mode excitation in a high-intensity linac

Radial deviation for the full Linac4:

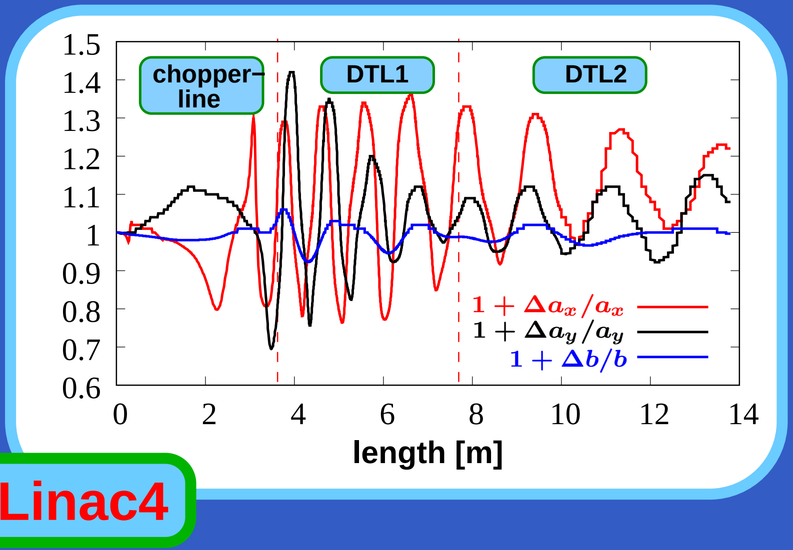


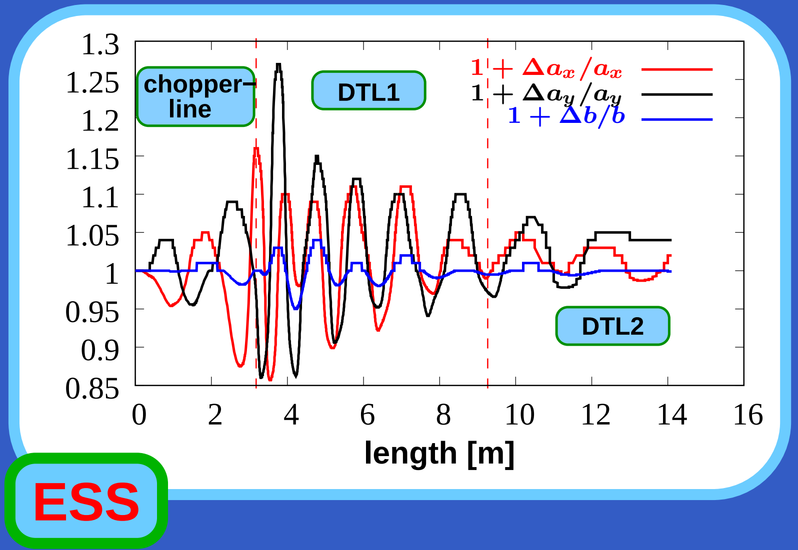
Δa_x, Δa_y, and Δb for the worst case in y (1% gradient variation)

- Statistical errors also result in core oscillation!
- The highest radial deviation compared to the matched case is observed after the chopper line in the first DTL tank!

Transverse Errors (radial deviation)

Worst case radial deviation for the Linac4 and ESS front-end, 1% gradient error:





$\Delta r_{t,max}$	42.0%
$\Delta \varepsilon_{t,max}$	37.4%
$\Delta \varepsilon_{t,av}$	3.3%
max. loss	< 5.5%

$\Delta r_{t,max}$	26.8%
$\Delta \varepsilon_{t,max}$	26.5%
$\Delta \varepsilon_{t,av}$	5.2%
max. loss	< 0.5%

Chopper lines are particularly vulnerable to statistical errors!
The subsequent structures must be able to cope with the considerable transition mismatch between chopper line and regular accelerating lattice.

Transverse Errors (observations)

- Statistical errors result in similar core oscillations as beam eigenmodes excited with initial mismatch ➠ the same theory for halo development applies for both cases (particle core model, parametric resonances, halo fixed-points), ➠ halo studies with initial mismatch are a sensible way of testing lattices,
- the chopper line disrupts the smooth focusing structure of RFQ and DTL and introduces strong transition mismatch which is enhanced by statistical errors,
- for all 4 error amplitudes, the same error sets (out of 500) produce the maximum emittance increase in all planes ➠ to estimate statistics for different error amplitudes one can run the worst case with different amplitudes and use the result to scale the curve for the average (or other) growth rates, (not applicable for losses).

Longitudinal Errors

Evaluation splits into two subjects:

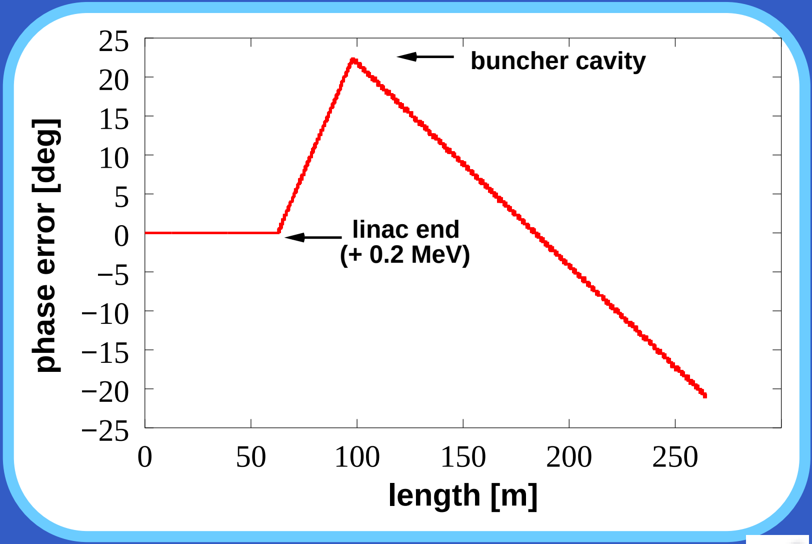
I emittance growth & radial deviation

- longitudinal halo,
- longitudinal losses (particles leaving the RF bucket).

II phase and energy jitter

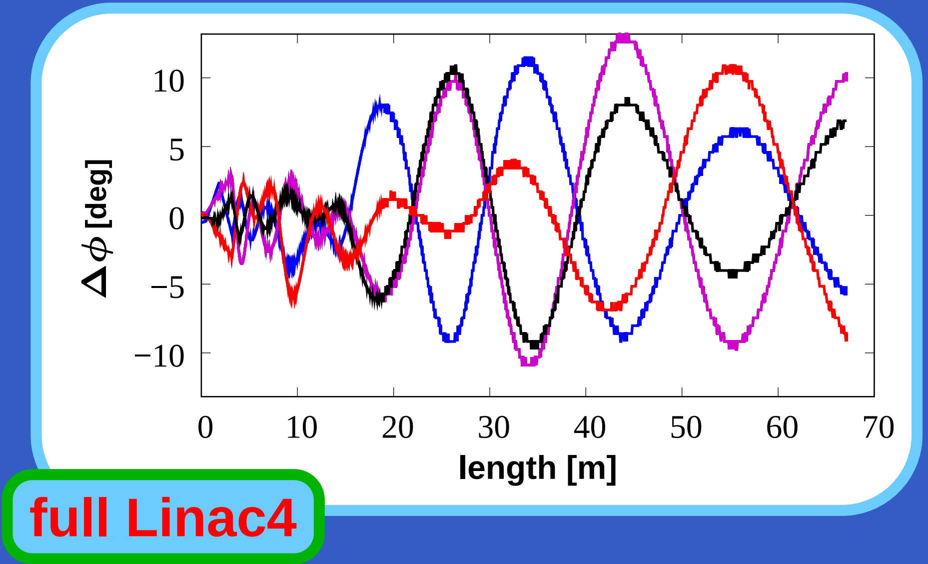
important if the linac beam enters **any** other lattice with RF systems (transport lines, rings, or further high energy linac sections).

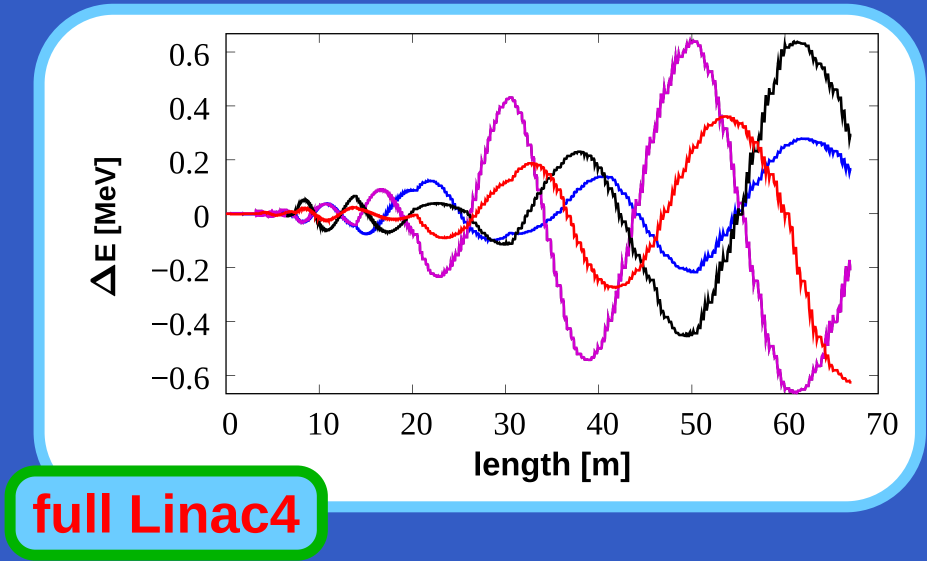
phase deviation in a transfer line with one buncher cavity, linac output: 120 MeV with + 0.2 MeV energy offset



Longitudinal Errors (phase/energy jitter)

Worst case examples from one error set (Linac4 with: 1.5% field error & 1.5° phase error):



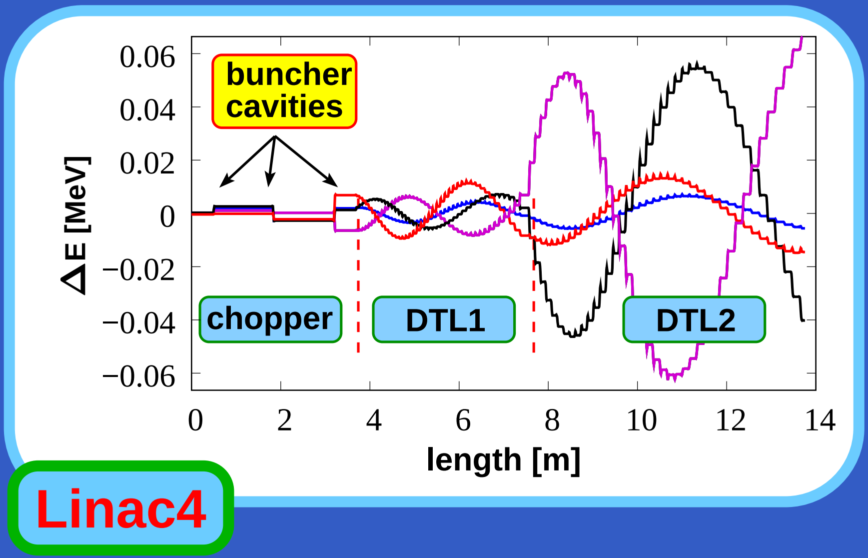


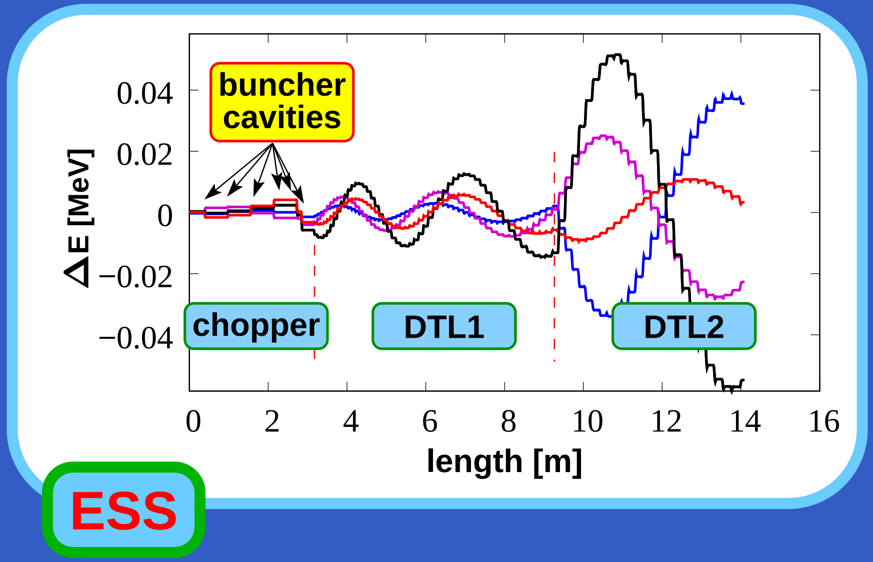
$$\Delta\phi = \phi_{err.} - \phi_{nom.} \qquad \Delta E = E_{err.} - E_{nom.}$$

➜ Worst case trajectories obtain large kicks at lattice transitions and/or transitions from one power source to the next.

Longitudinal Errors (phase/energy jitter)

worst case energy deviations for the Linac4 & ESS front-ends (1% field error, 1° phase error):



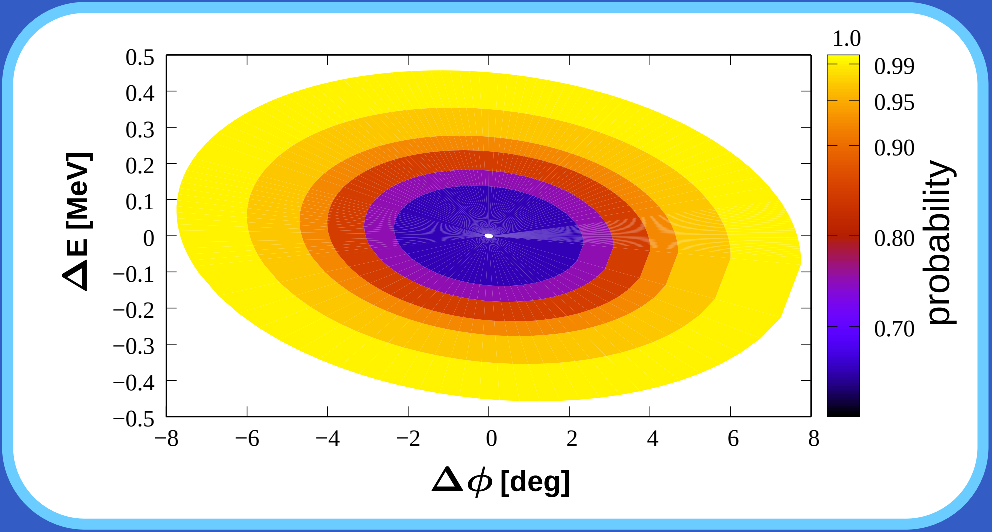


ΔE_{max}	66 kV
ΔE_{av}	22 kV
$\Delta \phi_{max}$	5.8°
$\Delta \phi_{av}$	2.1°
$\Delta \varepsilon_{l,max}$	6.7 %
$\Delta \varepsilon_{l,av}$	1.6 %
max. loss	< 4%

ΔE_{max}	58 kV
ΔE_{av}	18 kV
$\Delta \phi_{max}$	4.4°
$\Delta \phi_{av}$	1.6°
$\Delta \varepsilon_{l,max}$	7.2 %
$\Delta \varepsilon_{l,av}$	1.8 %
max. loss	< 0.4%

Longitudinal Errors (phase/energy jitter)

Probability plot for phase & energy jitter at the linac end ...

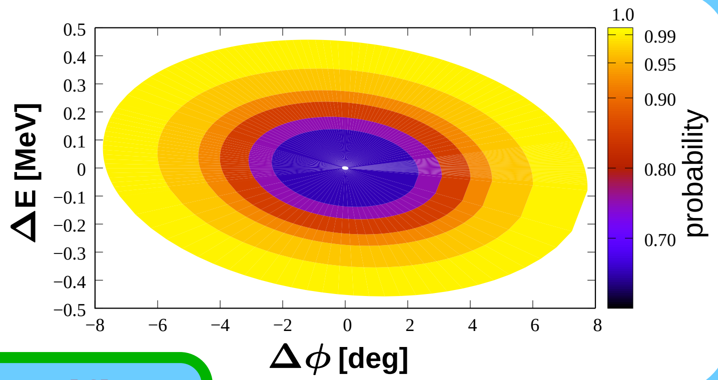


probability for the phase and energy level of the bunch center at the end of Linac4, 1% field error, 1° phase error

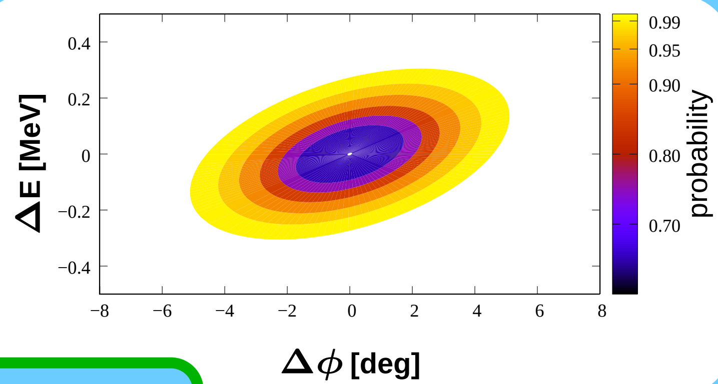
Together with the actual phase & energy width of the beam this plot provides an injection loss estimation for subsequent lattices with limited RF bucket sizes.

Longitudinal Errors (no. of power sources)

Experiment: reduce the no. of power sources in Linac4 by a factor of three and compare the results for 1% field error and 1° phase error:



16 amplifiers



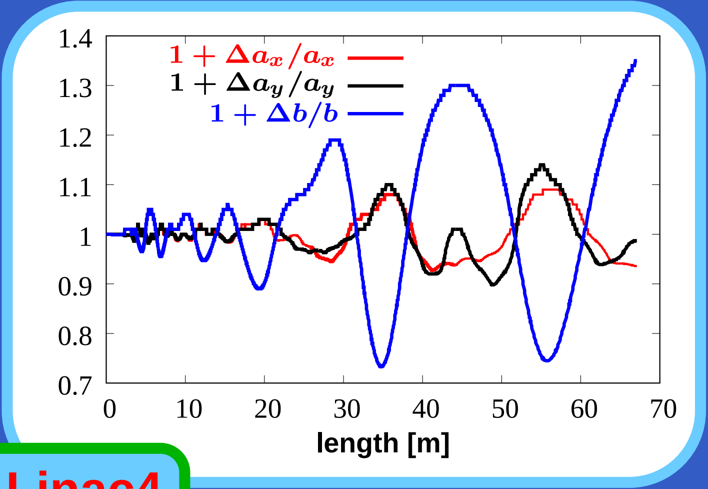
5 amplifiers

ΔE_{max}	478 keV
ΔE_{av}	168 keV
$\Delta \phi_{max}$	8.6°
$\Delta \phi_{av}$	3.7°
$\Delta \varepsilon_{l,max}$	19.4 %
$\Delta \varepsilon_{l,av}$	5.8 %

ΔE_{max}	281 keV
ΔE_{av}	99 keV
$\Delta \phi_{max}$	6.9°
$\Delta \phi_{av}$	2.6°
$\Delta \varepsilon_{l,max}$	7.4 %
$\Delta \varepsilon_{l,av}$	2.7 %

➜ **more than 50% reduction of longitudinal $\varepsilon_{r.m.s.}$ growth**

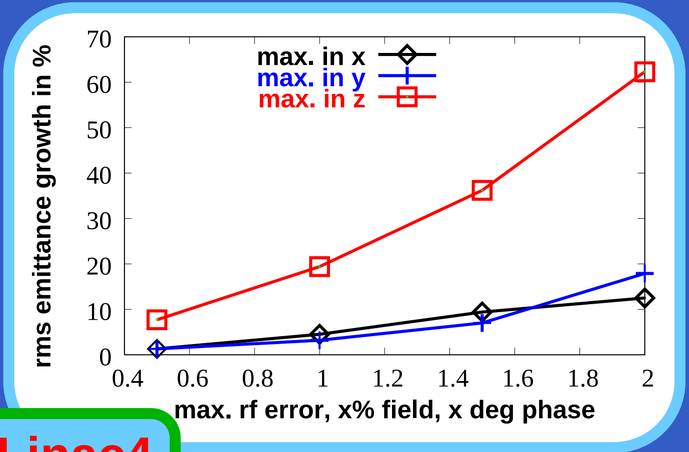
Longitudinal Errors (radial deviation)



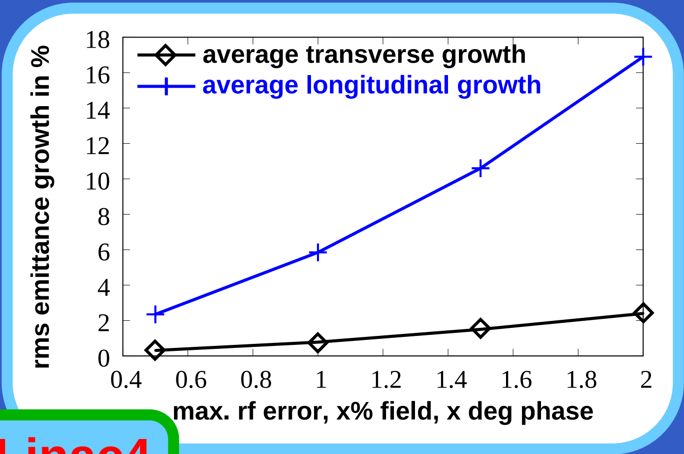
full Linac4

Δa_x, Δa_y, and Δb for the worst case in z (1% field error, 1° phase error)

Contrary to the transv. case the rad. deviations increase continuously.



full Linac4



full Linac4

maximum r.m.s. emittance increase

average r.m.s. emittance increase

Longitudinal Errors (observations)

- (For some cases) statistical RF errors seem to result in continuously increasing longitudinal core oscillations ⇒ danger of instability,
- longitudinal emittance increase is less worrying than the resulting phase & energy jitter,
- development of RF jitter and emittance growth depends strongly on the number of power of supplies and the number of RF gaps per power supply,
- in linac front-ends fewer power supplies seem to be preferable,
- due to the dependance of error development on the power splitting a generalized rule about emittance growth versus error amplitudes does not seem feasible (applies as well for the transverse case),
- long drifts between RF systems enhance RF jitter and emittance growth (compare CERN and ESS chopper line results, or transfer line).

Still to come...

- More statistical evaluation of the results,
- characterization of transverse profile changes due to statistical errors,
- dependance of transverse emittance growth on the number of magnets per power supply,
- RF and quadrupole alignment errors,
- combination of all error types.